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Baseline Testing of the Ultracapacitor Enhanced Photovoltaic Power Station

Dennis J. Eichenberg, John S. Kolacz, and Paul F. Tavernelli
Glenn Research Center, Cleveland, Ohio

November 2001

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BASELINE TESTING OF THE ULTRACAPACITOR ENHANCED PHOTOVOLTAIC POWER STATION

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SUMMARY

The NASA John H. Glenn Research Center is developing an advanced ultracapacitor enhanced photovoltaic power station. Goals of this effort include maximizing photovoltaic power generation efficiency and extending the life of photovoltaic energy storage systems. Unique aspects of the power station include the use of a solar tracker, and ultracapacitors for energy storage. The photovoltaic power station is seen as a way to provide electric power in remote locations that would otherwise not have electric power, provide independence from utility systems, reduce pollution, reduce fossil fuel consumption, and reduce operating costs. The work was done under the Hybrid Power Management (HPM) Program, which includes the Hybrid Electric Transit Bus (HETB), and the E-Bike. The power station complements the E-Bike extremely well in that it permits the charging of the vehicle batteries in remote locations. Other applications include scientific research and medical power sources in isolated regions. The power station is an inexpensive approach to advance the state of the art in power technology in a practical application. The project transfers space technology to terrestrial use via non-traditional partners, and provides power system data valuable for future space applications. A description of the ultracapacitor enhanced power station, the results of performance testing and future power station development plans is the subject of this report. The report concludes that the ultracapacitor enhanced power station provides excellent performance, and that the implementation of ultracapacitors in the power system can provide significant performance improvements.

INTRODUCTION

The NASA Glenn Research Center initiated baseline testing of the ultracapacitor enhanced power station as an excellent opportunity to transfer technology from the aerospace and military industries to a commercial venture. The project is seen as a way to provide electric power generation in remote locations that would otherwise not have electric power, provide independence from utility systems, reduce pollution, reduce fossil fuel consumption, and reduce operating costs for power generations systems.

The NASA Glenn Research Center provides overall project coordination and is responsible for testing the power station. This includes instrumenting the power station and developing instrumentation and control programs. Wherever practical, off-the-shelf components have been integrated into the test configuration.

TEST OBJECTIVES

Testing of the ultracapacitor enhanced power station was performed at the NASA Glenn Research Center. Of particular interest are power generation capacity, and energy storage capacity. The performance of the various power station components, especially the photovoltaic panels, solar tracker, energy storage system, and inverter are also of interest.

POWER STATION DESCRIPTION

The ultracapacitor enhanced photovoltaic power station is a high performance, state of the art power generation system. The power station is shown in Figures 1 and 2 and described in detail in Appendix A. The block diagram of the power station is shown in Figure 3.

Power is generated from two 5'x2', 16.9 volt, 120 Watt, all weather photovoltaic panels. The photovoltaic panels are mounted on a photovoltaic panel solar tracker for tracking the path of the sun to improve efficiency. The tracker is a non-energy-consuming device that operates from the heating of a thermal medium to change the panel position. The tracker can increase the total energy produced by the photovoltaic panels by up to 50% more than the panels on a fixed mount.

Power from the photovoltaic panels is taken to the power station control enclosure. Within the control box are the remainder of the power station components. Jumper panels are provided to facilitate reconfiguration for various applications.

The energy storage system consists of four 50 farad, 18 volt ultracapacitors to store electrical energy. For the tests, they were connected in parallel for a 200 farad, 18 volt capacitor bank or in series/parallel for a 50 farad, 36 volt bank.

A 250-Watt, 60 Hz sine wave inverter is provided for powering various ac loads. A sine wave inverter was used to minimize noise generation, and provide a clean power source to the load.

The E-Bike battery charger is built into the battery pack. The charger is rated at 24 volts, 1.6 amps DC. The complete battery pack including the charger is shown in Figure 4. The battery pack is quickly removed from the vehicle if so desired. This permits the quick installation of another battery pack, as well as charging of the battery pack within the power station control enclosure.

Fig. 1 – Photovoltaic Power Station at NASA Glenn Research Center

NASA
C-2001-986

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John H. Glenn Research Center at Lewis Field

Fig. 2 – Photovoltaic Power Station Control Enclosure

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C-2001-987

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John H. Glenn Research Center at Lewis Field

Fig. 3 – Photovoltaic Power Station Block Diagram

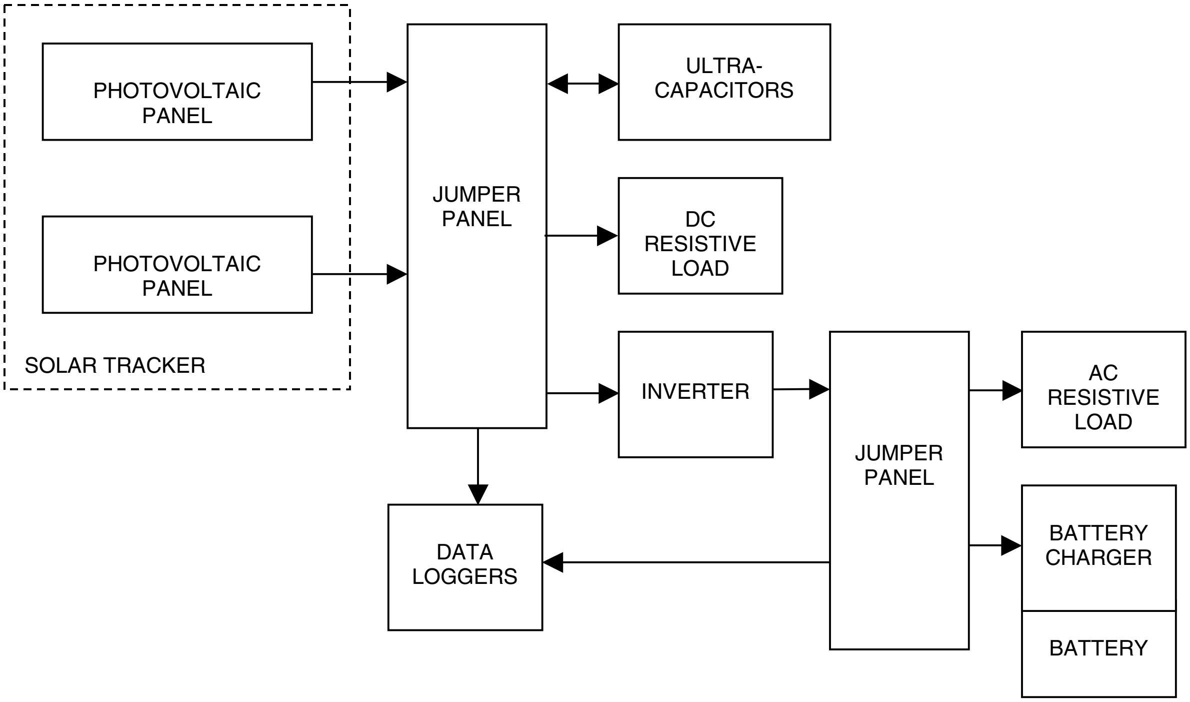
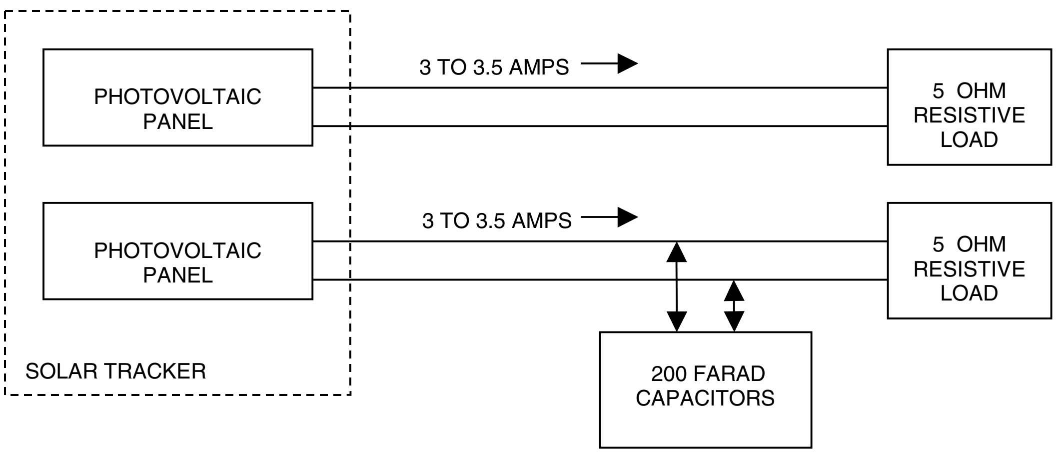


Fig. 4 – Battery Charger and Battery

TEST CONFIGURATIONS

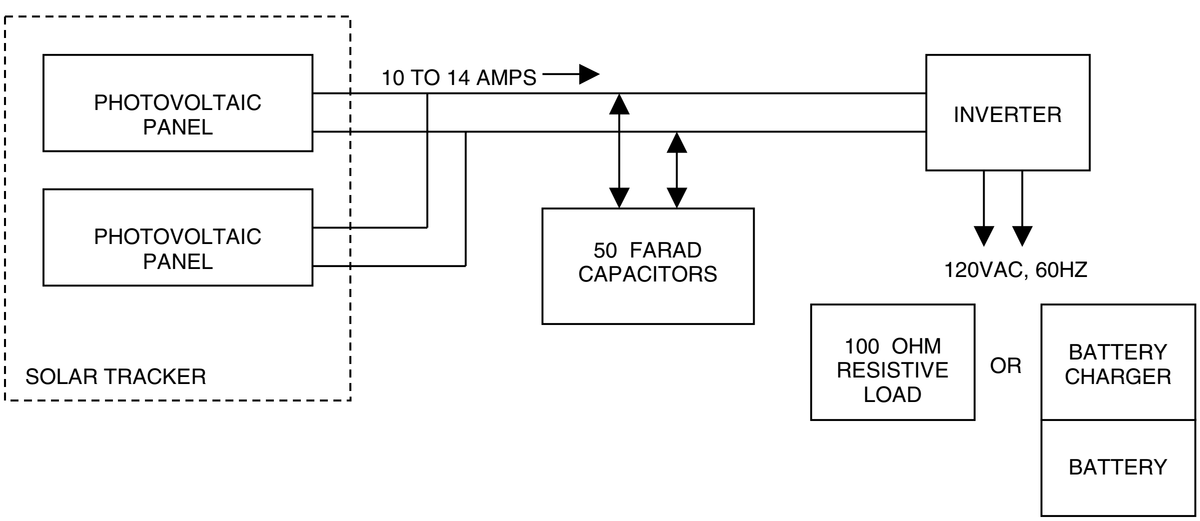
The DC test configuration of the ultracapacitor enhanced power station is shown in Figure 5. It was configured to compare the characteristics of photovoltaic-produced power without ultracapacitor energy storage, versus the characteristics of photovoltaic-produced power with ultracapacitor energy storage. A 5-ohm resistive load was connected to each system. This permits each panel to receive the same amount of solar energy, and supply power to the same size load.

Fig. 5 – DC Test Configuration



The AC test configuration of the ultracapacitor enhanced power station is shown in Figure 6. In this case, the two 120 Watt photovoltaic panels were connected in parallel to operate a 250 Watt inverter with different loads. Ultracapacitors were used for all tests because it was impossible to start the loaded inverter with only the photovoltaic panels.

Fig. 6 – AC Test Configuration



INSTRUMENTATION

The power station was instrumented to measure the load voltage and the load current of each of the two systems. Additional channels measured ambient temperature, each photovoltaic panel temperature, and the internal control box temperature. An optical pyrometer was used to record the solar insolation during testing. Data were sent to an on-board digital data acquisition system. The sample rate was once a minute. The data was downloaded to a personal data assistant (PDA) at the power station. The data was then downloaded from the PDA to a desktop PC. The instrumentation configuration is described in Appendix B.

TEST MATRIX

The tests described in this report were conducted at the NASA Glenn Research Center in Cleveland, Ohio from June to August 2001.

Tests 1 to 3 were conducted to characterize power station dc performance under various conditions. Test 4 was conducted to characterize performance using capacitors, inverter and resistive load. Lastly, Test 5 was conducted to characterize battery charging with an inverter. See Table 1.

Table 1 – Photovoltaic Power Station Test Matrix

Test Number	*DC Power Source*	*Capacitor (Farads)*	*Sky Conditions*	*Tracking Engaged*	*Test Load*
1a	120W PV	0	Clear	Yes	5-ohm dc load.
1b	120W PV	200	Clear	Yes	5-ohm dc load.
2a	120W PV	0	Partly Cloudy	Yes	5-ohm dc load.
2b	120W PV	200	Partly Cloudy	Yes	5-ohm dc load.
3	120W PV	200	Clear	No	5-ohm dc load.
4	240W PV	50	Clear	Yes	Inverter & 100-ohm ac load.
5	240W PV	50	Clear	Yes	Inverter & Battery Charger.

TEST RESULTS

Test 1 - DC Load Test With Clear Sky Conditions

As shown in Figures 7 and 8, the differences between the two systems only appear at the beginning and end of the day. The ultracapacitors are charging in the morning and pulling the system voltage down. In the afternoon, when the panel output starts to drop, the ultracapacitors continue to provide power to the load until discharged. This illustrates one feature of combining photovoltaics and ultracapacitors. If it is necessary to power a load overnight, a properly-sized photovoltaic and ultracapacitor system would be capable of performing that task.

Fig. 7 – Photovoltaic System Voltages With Clear Sky Conditions

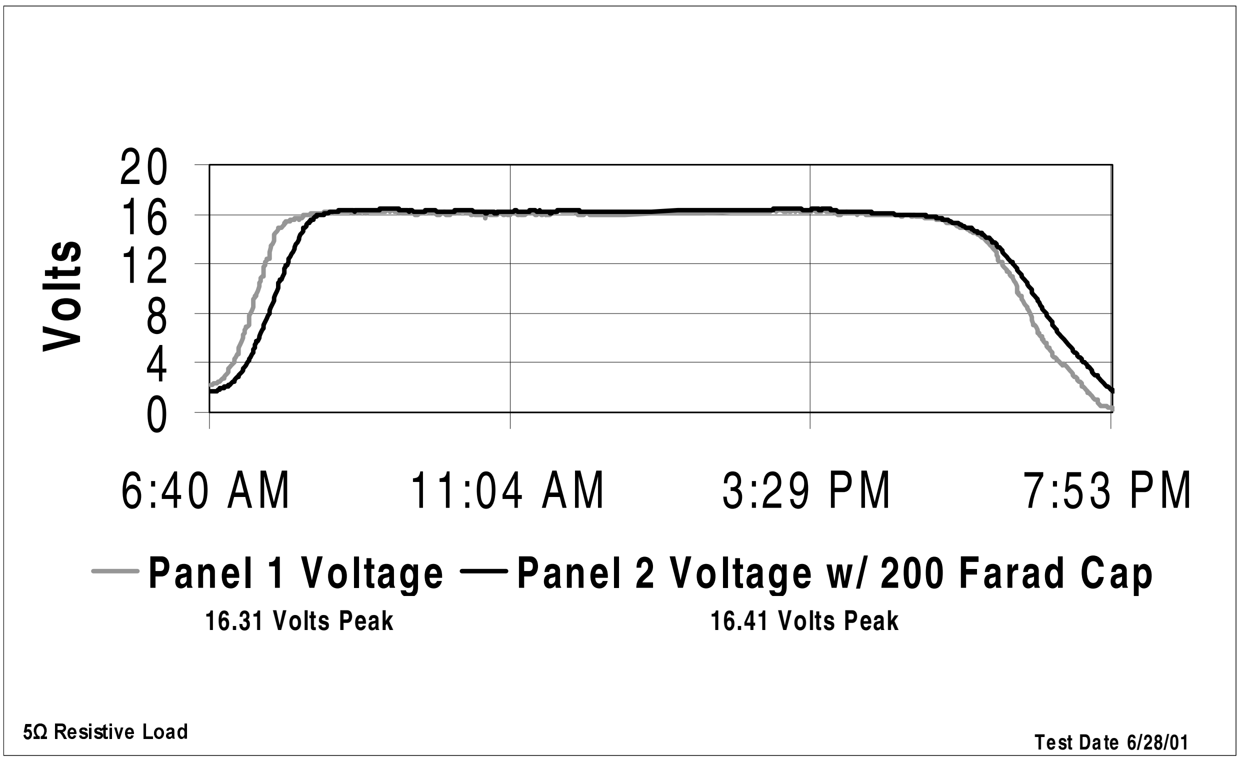


Fig. 8 - Photovoltaic System Currents With Clear Sky Conditions

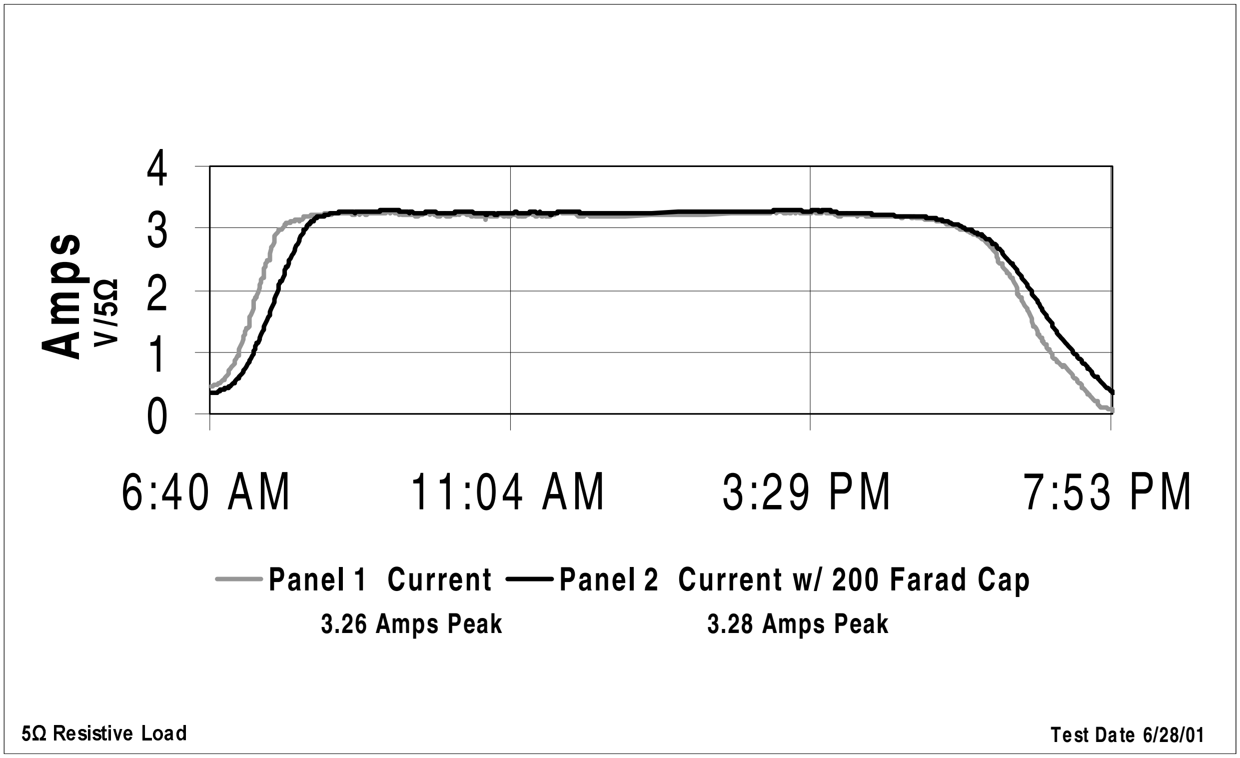
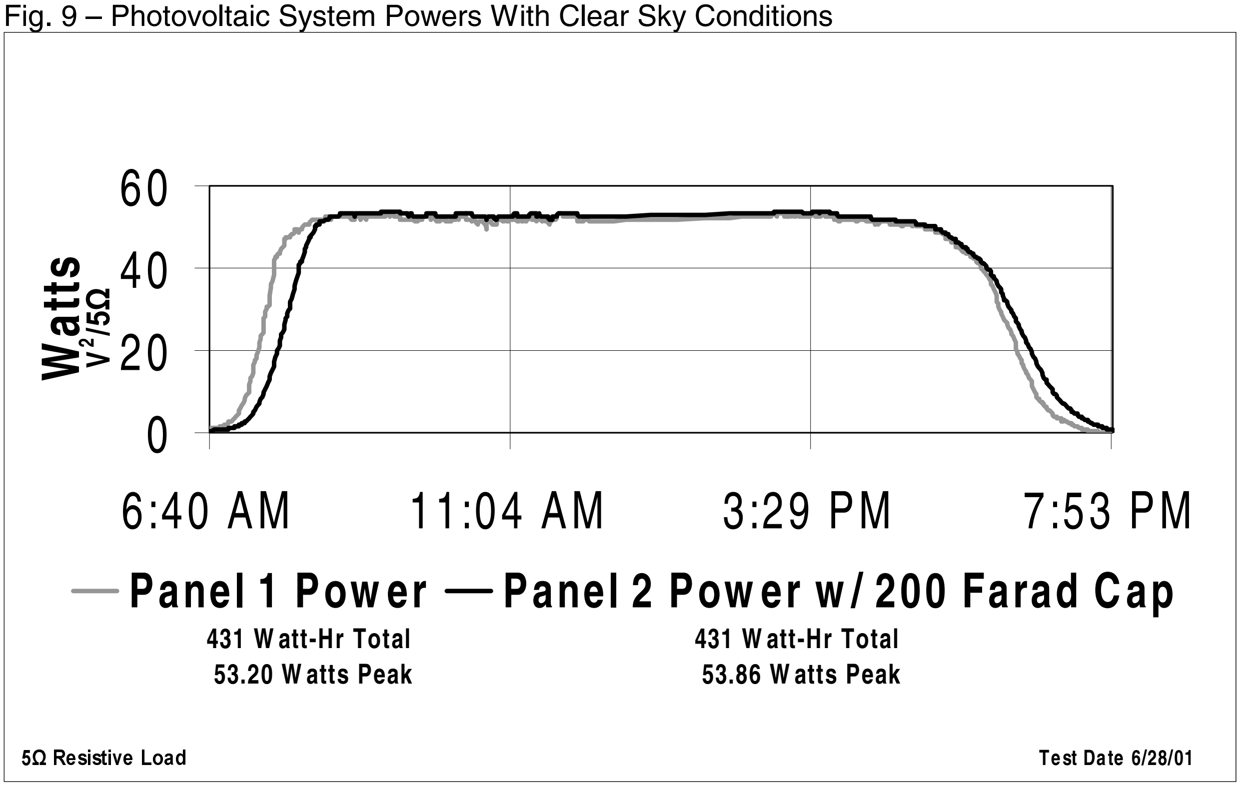


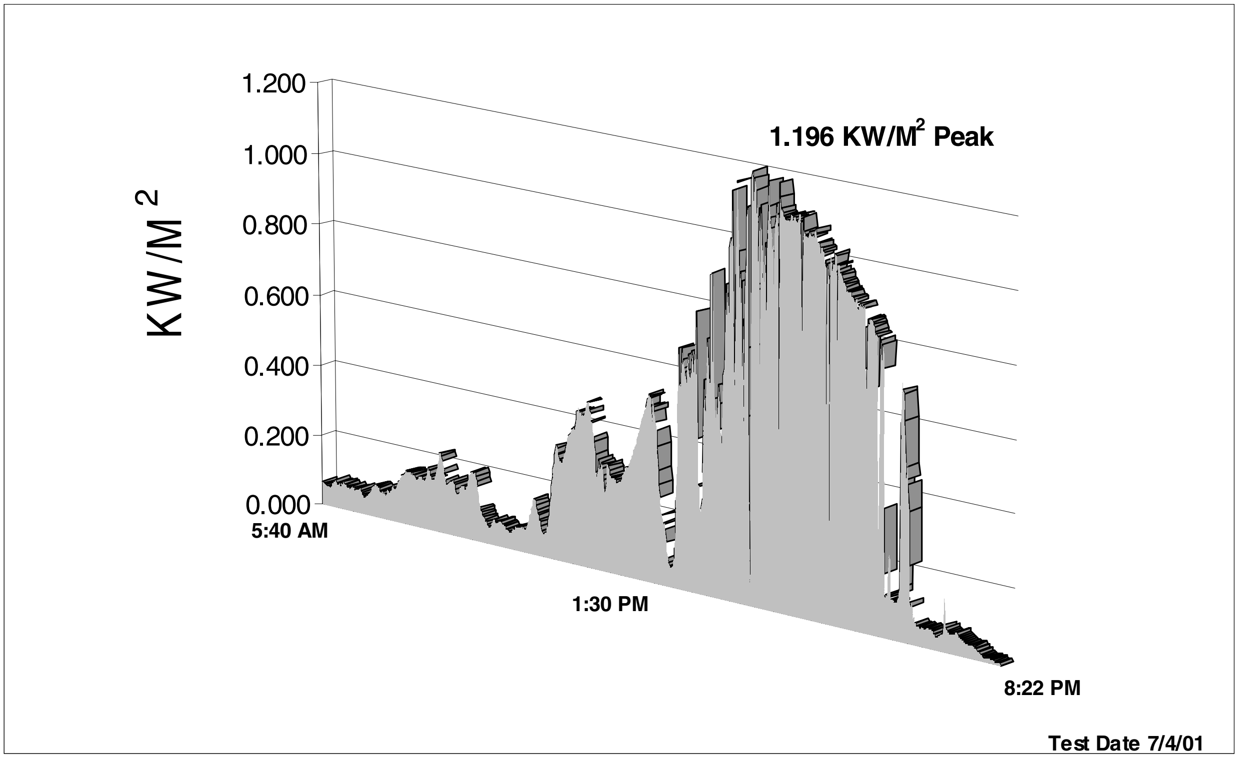
Fig. 9 – Photovoltaic System Powers With Clear Sky Conditions



Test 2 - DC Load Test With Partly Cloudy Sky Conditions

As shown in the following figures, the addition of a large ultracapacitor provides valuable short-term energy storage for a photovoltaic system. The solar radiation available to the systems is shown in Figure 10. Note that there were several times between 3:00 and 5:00 PM when clouds caused the available radiation to drop to only 200 watts/meter. [2]

Fig. 10 – Solar Radiation With Partly Cloudy Sky Conditions



Figures 11 through 13 show the voltages, currents, and power for the two photovoltaic systems under this varying solar radiation. Although the total energy was about the same, the voltage swings for the capacitor-equipped system were greatly reduced. The data in Table 2 illustrates this result. The shaded areas highlight two times when the solar radiation dropped significantly due to cloud cover. Without the capacitor (Panel 1), the system voltage dropped from 16.60 to 6.64 volts and 16.50 to 8.40 volts. With the capacitor (Panel 2), the voltage dropped from 16.5 to 15.72 volts and 16.41 to 16.01 volts. This would be advantageous for a load that requires a minimum voltage to operate.

Table 2 – Photovoltaic System Voltage Data for 7/4/01

Date & Time	Panel 1 Voltage	Panel 2 Voltage	Date & Time	Panel 1 Voltage	Panel 2 Voltage
7/4/01 3:30 PM	16.31	16.5	7/4/01 4:24 PM	16.41	16.5
7/4/01 3:31 PM	16.21	16.41	7/4/01 4:25 PM	16.41	16.5
7/4/01 3:32 PM	16.41	16.41	7/4/01 4:26 PM	16.41	16.41
7/4/01 3:33 PM	16.6	16.5	7/4/01 4:34 PM	16.5	16.31
7/4/01 3:34 PM	16.6	16.5	7/4/01 4:35 PM	16.5	16.41
7/4/01 3:35 PM	6.64	16.41	7/4/01 4:36 PM	15.82	16.41
7/4/01 3:36 PM	11.62	15.72	7/4/01 4:37 PM	16.5	16.41
7/4/01 3:37 PM	16.8	16.11	7/4/01 4:38 PM	8.4	16.01
7/4/01 3:38 PM	16.6	16.31	7/4/01 4:39 PM	16.7	16.01
7/4/01 3:39 PM	16.5	16.41	7/4/01 4:40 PM	16.6	16.21
7/4/01 3:47 PM	16.41	16.5	7/4/01 4:41 PM	16.5	16.31
7/4/01 3:48 PM	16.41	16.5	7/4/01 4:42 PM	16.6	16.41
7/4/01 3:49 PM	16.41	16.5	7/4/01 4:43 PM	16.6	16.5
7/4/01 3:50 PM	16.41	16.5	7/4/01 4:44 PM	16.6	16.6
7/4/01 3:51 PM	16.5	16.5	7/4/01 4:45 PM	16.6	16.6

Fig. 11 – Photovoltaic System Voltages With Partly Cloudy Sky Conditions

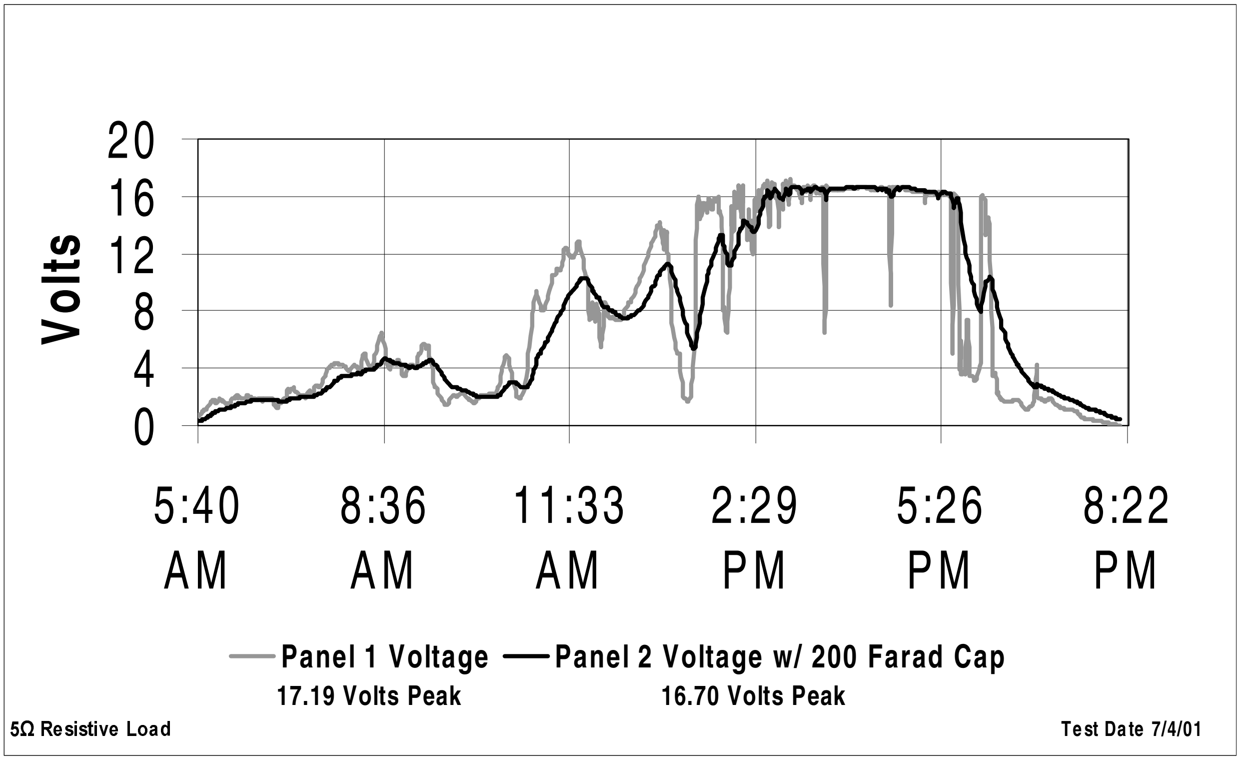


Fig. 12 – Photovoltaic System Currents With Partly Cloudy Sky Conditions

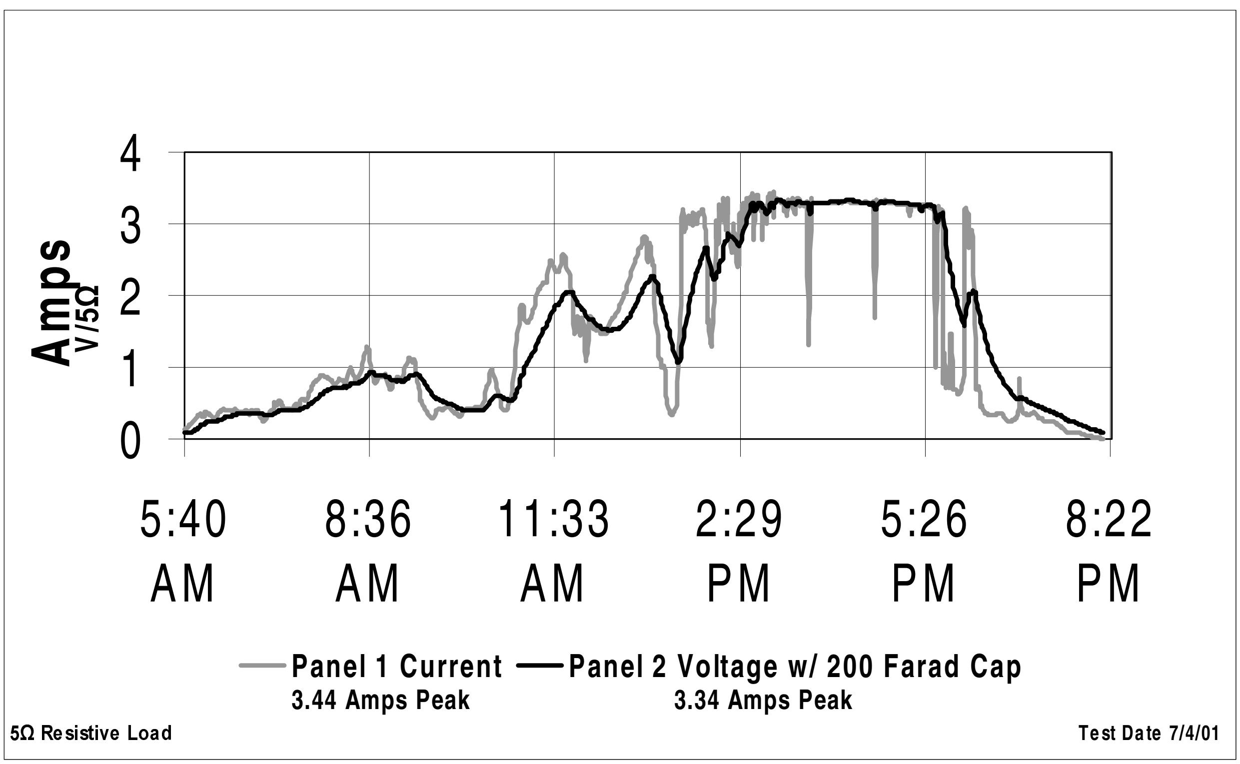
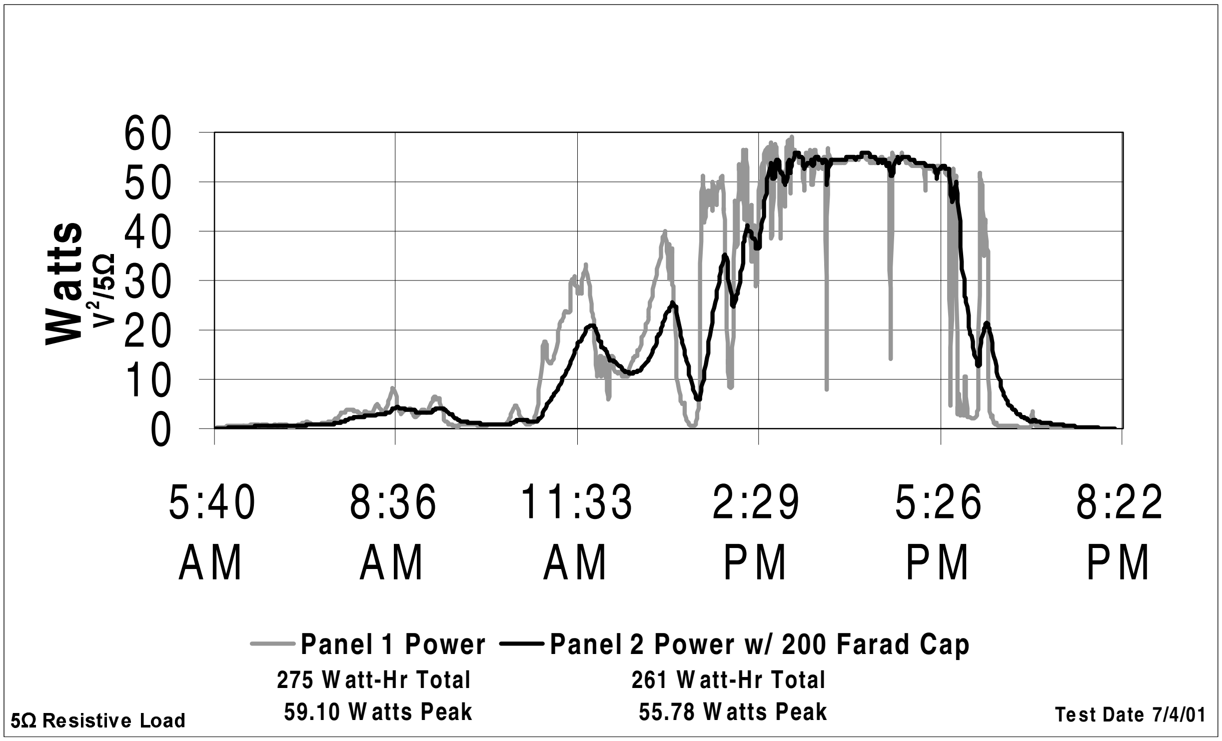


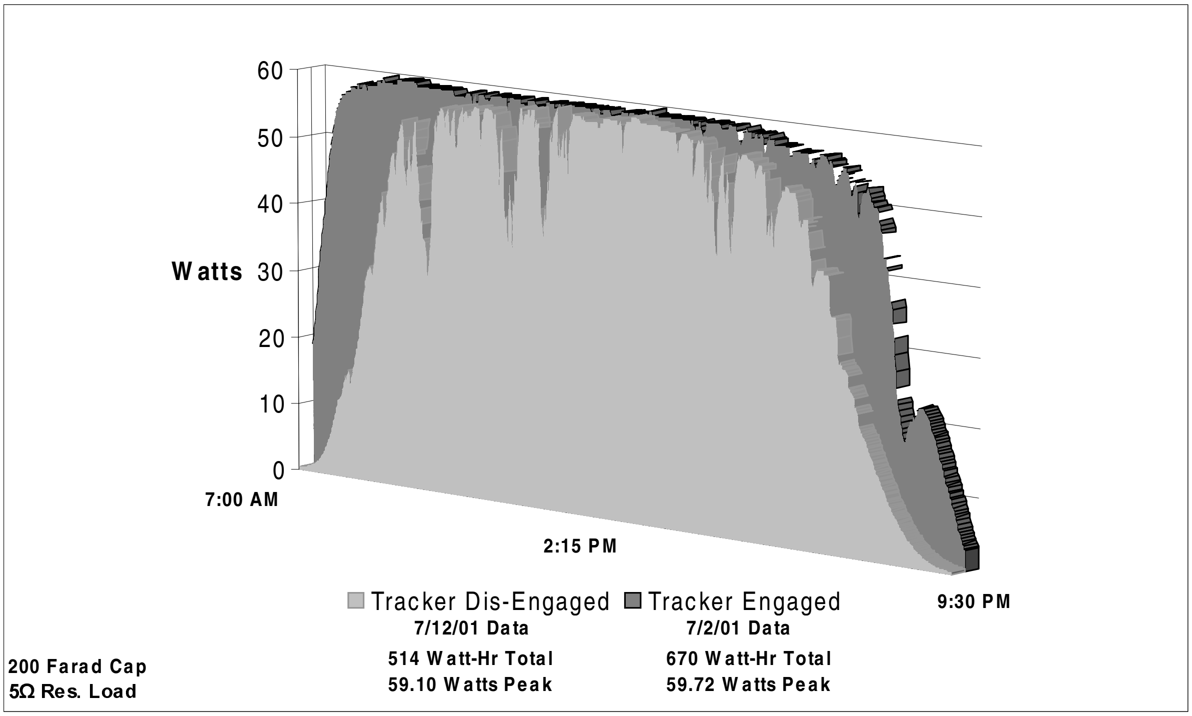
Fig. 13 – Photovoltaic System Powers With Partly Cloudy Sky Conditions



Test 3 - DC Load Test With Tracking Disabled

For this test, the solar tracker was disabled and the photovoltaic panels were placed in a fixed due south position. Figure 14 shows that the daily total energy (Watt-hour) produced with a 5 ohm load was reduced from 670 Watt-hour to 514 Watt-hour under clear conditions.

Fig. 14 – Photovoltaic System Energy With and Without Tracking



Test 4 - AC Load Test With Resistive Load

For the next test, a 250 Watt inverter with a 100 ohm resistor was used as the system load. With the inverter output at 125VAC, this is a 156 Watt load. As illustrated in Figures 15 through 17, it was difficult to operate the inverter consistently. Like most commercially available inverters, the one tested operates within a relatively narrow voltage range (essentially the 12 volt automotive range). It is also protected from under and over-voltage by circuits which shut off the inverter. The photovoltaic system that powered the inverter has no voltage regulation. A comparator circuit was used to enable the inverter when the system voltage was within the inverter specifications. Unfortunately, the 100 ohm load was large enough to discharge the capacitor and pull down the system voltage to the point where the inverter shut off. The system voltage would then recover because of the photovoltaics and the cycle would repeat. By adjusting the comparator trigger voltage, the time between cycles could be increased, but the inverter would eventually shut off.

Fig. 15 – Photovoltaic System DC Voltage with Inverter and 100 Ohm Load

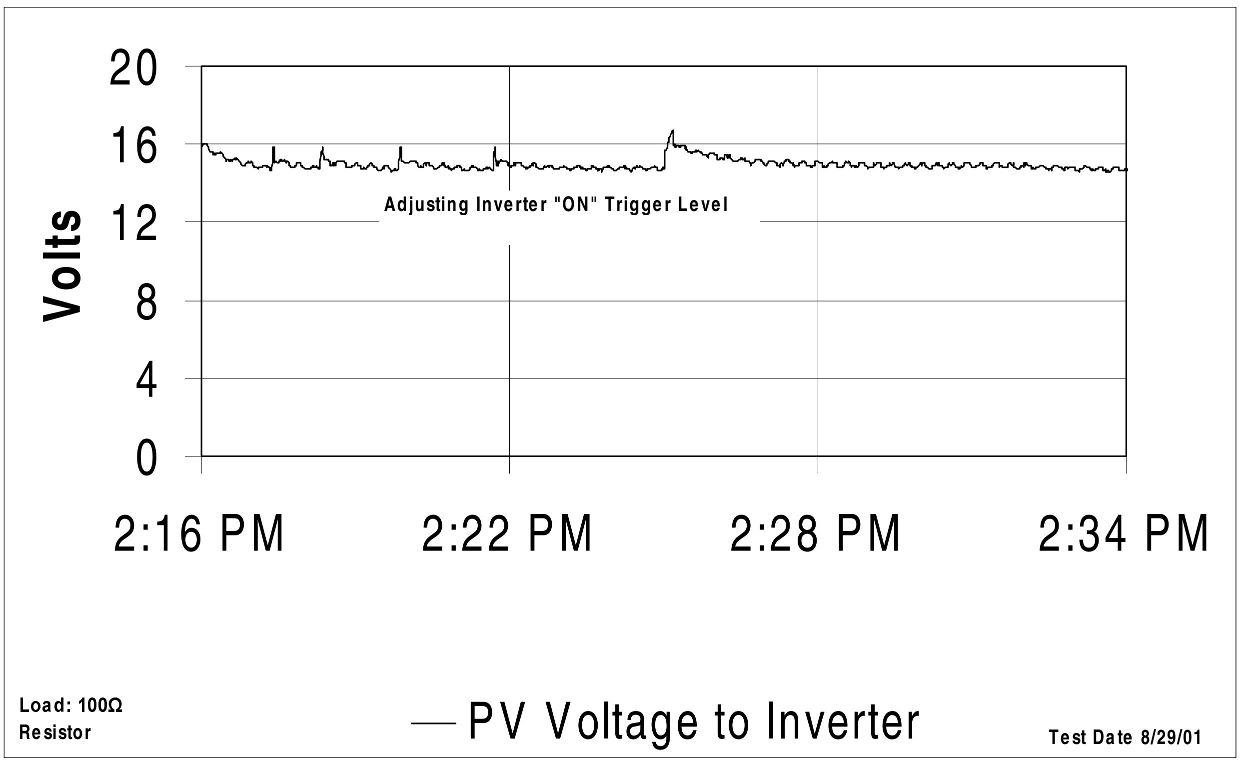


Fig. 16 – Photovoltaic System DC Current with Inverter and 100 Ohm Load

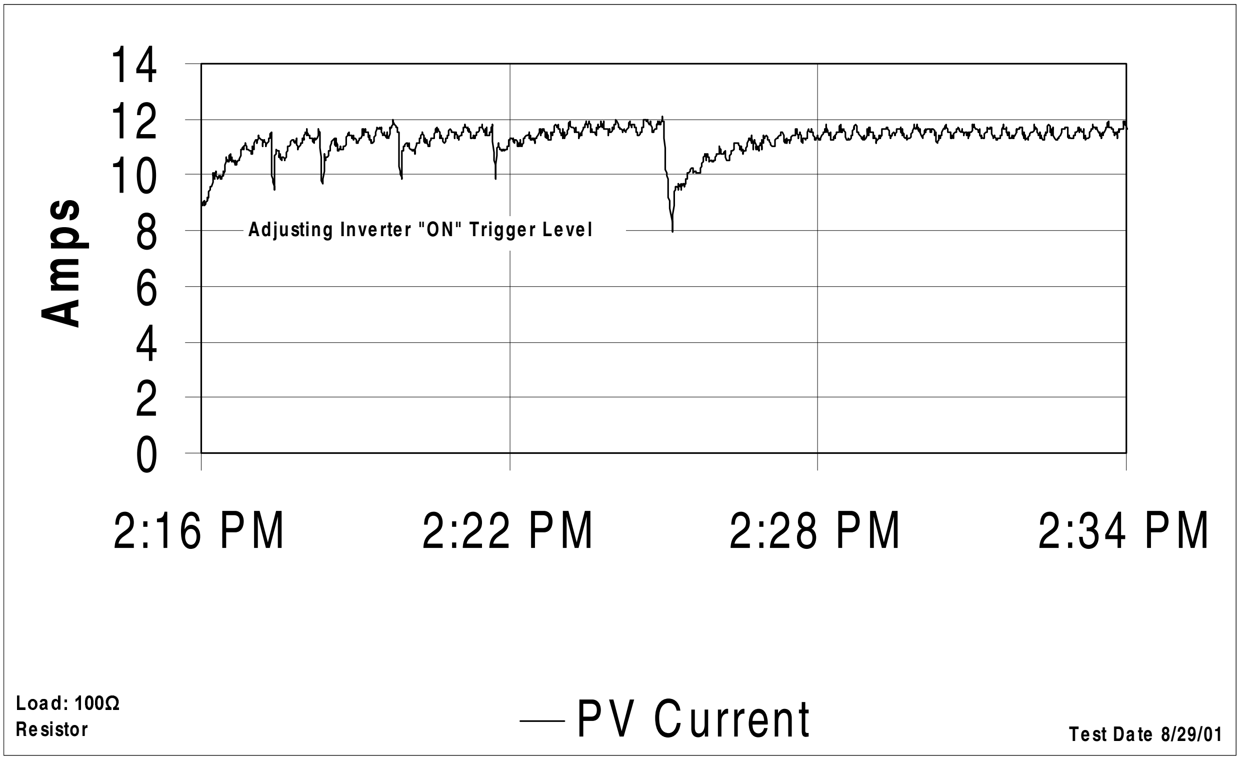
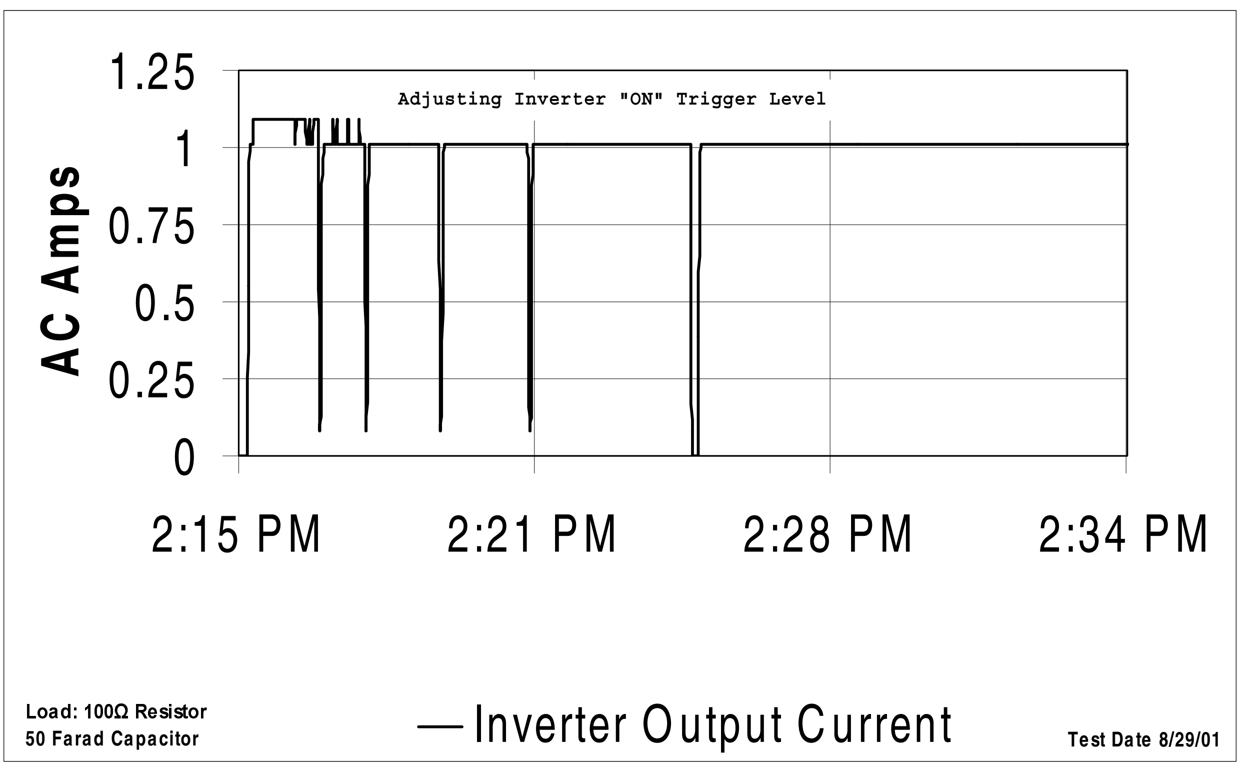


Fig. 17 – Photovoltaic System AC Current with Inverter and 100 Ohm Load



Test 5 - AC Load Test With Battery Charger

For the last test, an AC-powered battery charger and battery combination was operated with the PV system. This battery is the power source for EV Global's E-Bike and is a good example of a real-world load for this size PV system. Unlike the 100 ohm resistor, the battery charger did not reduce the system voltage enough to cause the inverter to shut off. The following figures show that the charger operated satisfactorily with the PV system.

Fig. 18 – Photovoltaic System DC Voltage With Inverter and Battery Charger

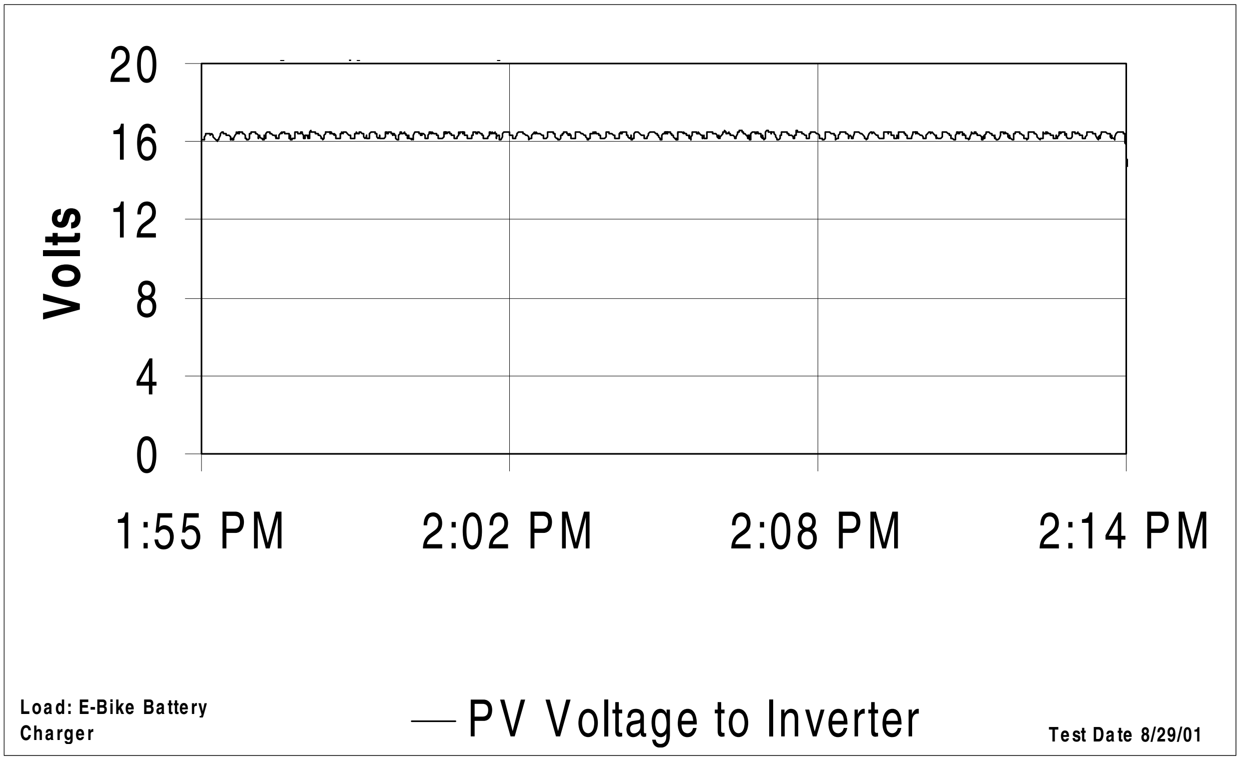


Fig. 19 – Photovoltaic System DC Current With Inverter and Battery Charger

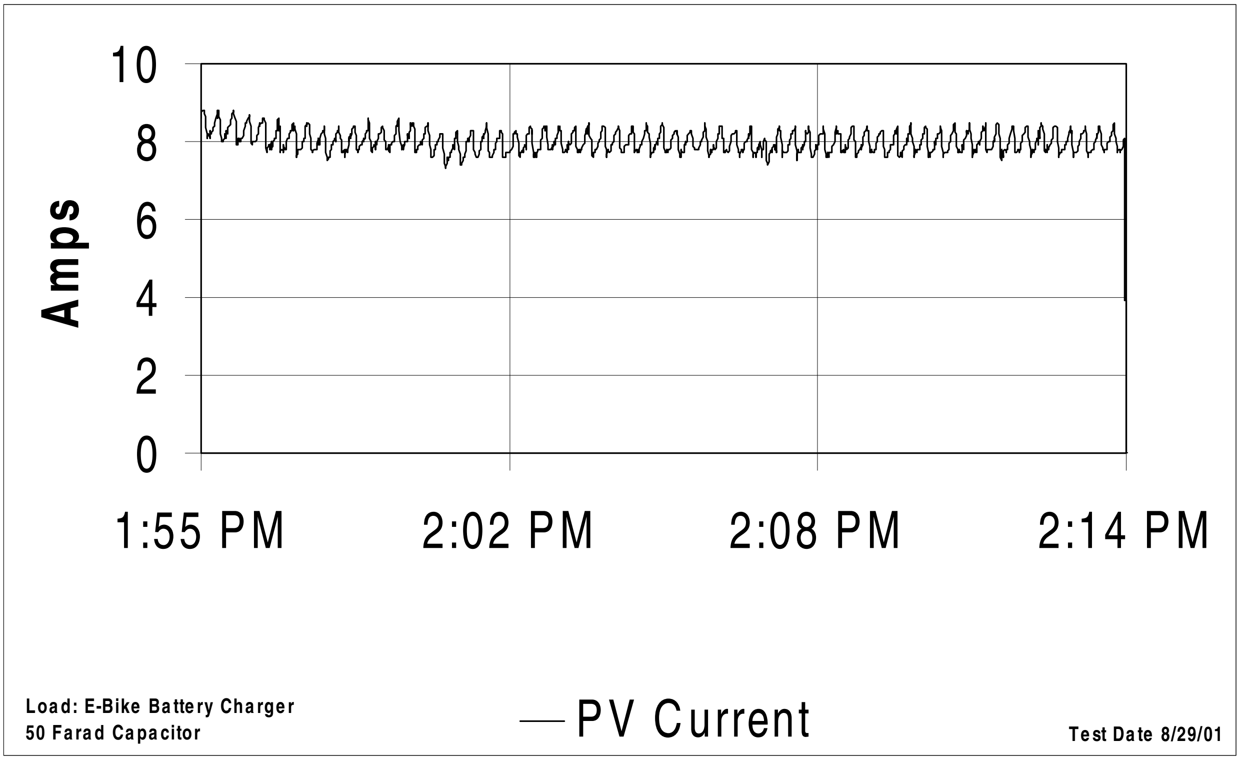
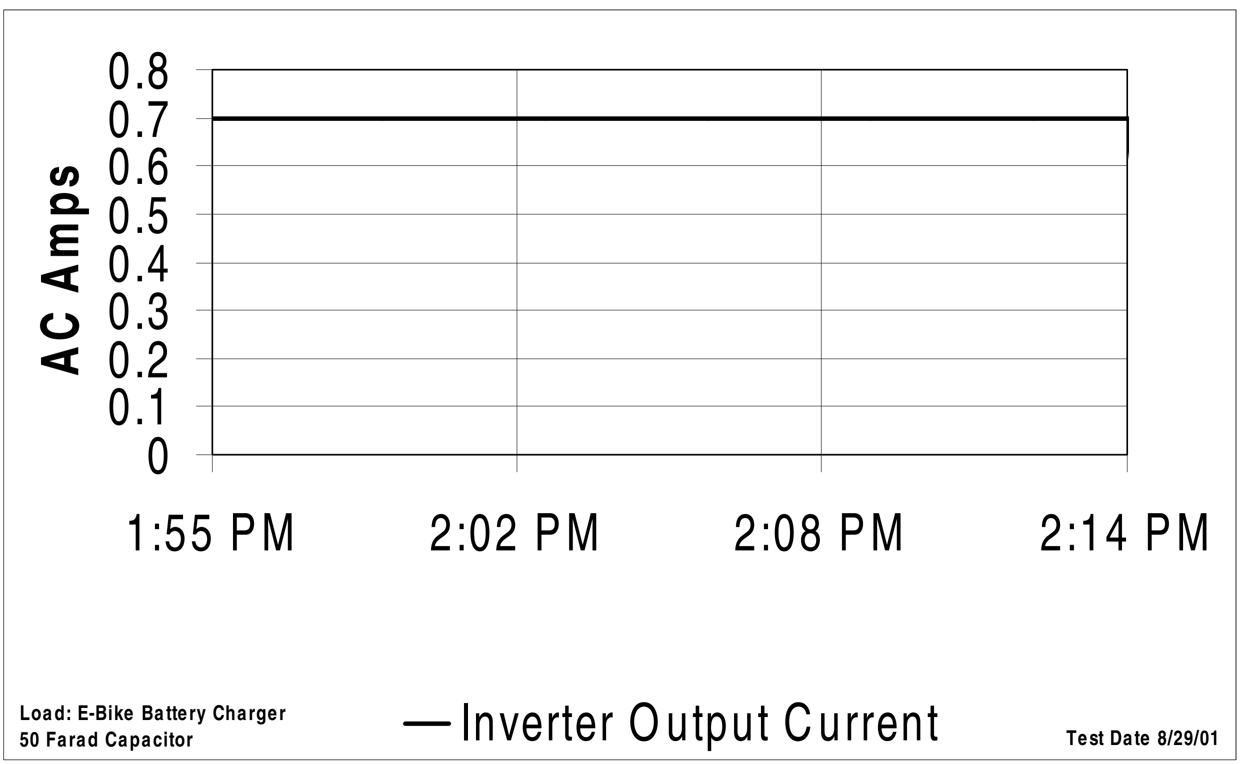


Fig. 20 – Photovoltaic System AC Current With Inverter and Battery Charger



CONCLUDING REMARKS

The ultracapacitor enhanced photovoltaic power station as tested and described in this report is comprised of commercially available components. Testing performed with and without ultracapacitors show the change in photovoltaic system characteristics caused by the addition of ultracapacitors. In particular, the comparison tests reveal improvements in photovoltaic system performance which are created by the ultracapacitors' short-term energy storage characteristics. Testing with an inverter and large resistive load illustrates the difficulties presented by a device that operates within a narrow voltage range. Operating the inverter with a smaller load, the battery charger, shows that the photovoltaic and ultracapacitor system can function well in a real-world situation.

APPENDIX A

POWER STATION SUMMARY DATA SHEET

1.0 Photovoltaic Panel	
1.1 Manufacturer	Kyocera
1.2 Type	PV2898
1.3 Configuration	Multicrystal modules, two panels on station
1.4 Voltage	16.9 volts dc each
1.5 Power	120 Watts each
1.5 Dimensions	56.0”x25.7” each
1.6 Weight	26.2 lbs. each
2.0 Photovoltaic Panel Solar Tracker	
2.1 Manufacturer	Zomeworks
2.2 Type	TM3855
2.3 Configuration	Non-energy-consuming thermal activation
2.4 Dimensions	Accommodates two 56.0”x25.7” panels
2.5 Weight	82 lbs.
3.0 Ultracapacitor	
3.1 Manufacturer	Alumapro
3.2 Type	18PP-8/0,006
3.3 Configuration	Dual layer, electrochemical, four in parallel
3.4 Voltage	18 volts dc
3.5 Capacitance	50 farads each, 200 farads total
3.6 Energy	8.1 kilojoules each, 32.4 kilojoules total
3.7 Dimensions	6.5”x7.0”x3.25” each
3.8 Weight	10 lbs. each, 40 lbs. total
4.0 Inverter	
4.1 Manufacturer	Exeltech
4.2 Type	XP-2-1-1-6-0-X7
4.3 Configuration	True sine wave output inverter
4.4 Input	12 volts dc
4.5 Output	117 volts ac, 2.1 amps ac, 60 Hz
4.6 Dimensions	
4.7 Weight	10 lbs.

APPENDIX B

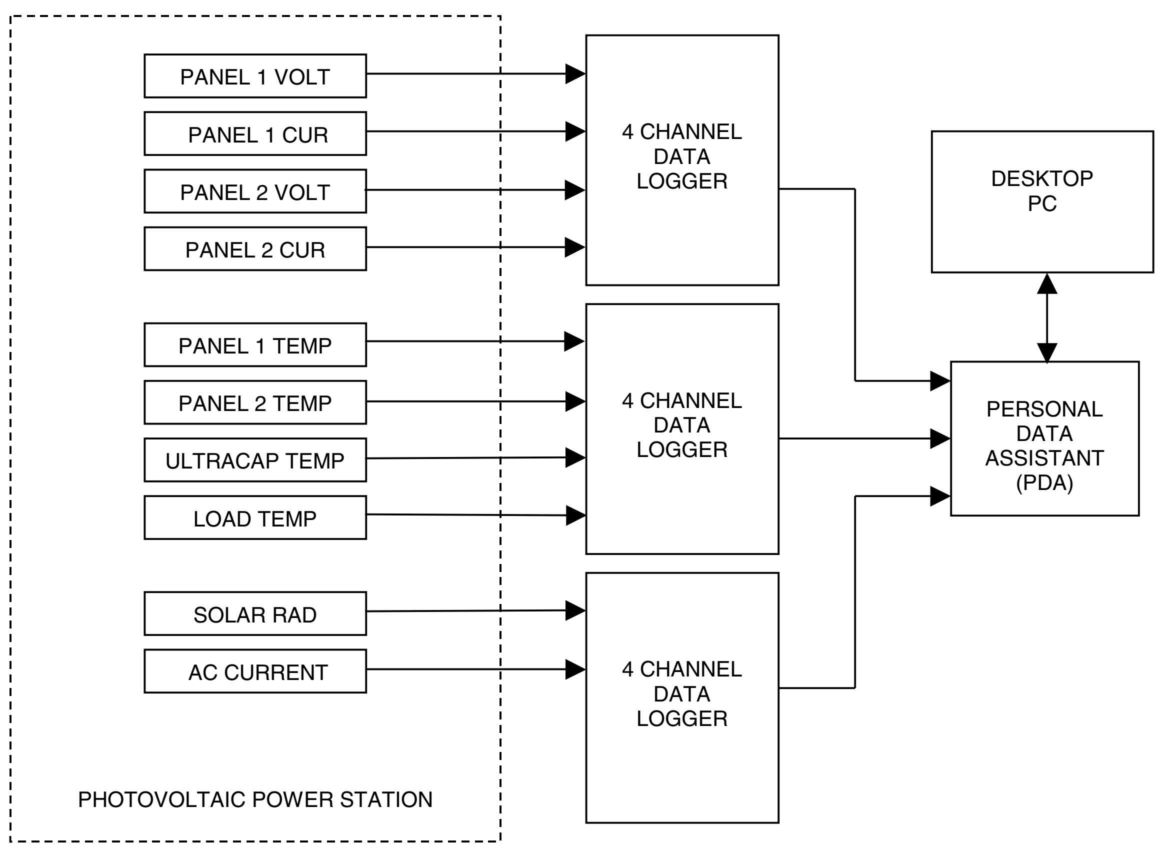
DESCRIPTION OF THE INSTRUMENTATION SYSTEM

A block diagram of the instrumentation system is shown in Fig. B-1.

The ultracapacitor enhanced photovoltaic power station has an integral instrumentation system. The instrumentation system includes three portable data loggers. Each data logger has four analog inputs. The first data logger monitors the dc load voltage and current of each of the two photovoltaic panels. The second data logger monitors the temperature of each photovoltaic panel, as well as the ambient temperature, and the internal cabinet temperature. The third data logger monitors the solar radiation and AC current to drawn by inverter loads. These data are sampled at one sample per minute and stored on the data loggers. This data is downloaded weekly to a personal data assistant taken to the photovoltaic power station. The personal data assistant is then transported to the desktop PC where the data is downloaded via a serial interface.

All voltages are derived from voltage dividers. DC currents are derived from current shunts. AC current is derived from a Hall-effect transducer. All temperatures are derived from active semiconductor temperature probes.

Fig. B-1 – Ultracapacitor Enhanced Photovoltaic Power System Instrumentation System



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